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GRAPHICAL REPRESENTATION OF INTERCOOLER PARAMETERS

AND PERFORMANCE AT ALTITUDES FROM

25,000 TO 60,000 FEET

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GRAPHICAL REPRESENTATION OF INTERCOOLER PARAMETERS AND PERFORMANCE AT ALTITUDES FROM 25,000 TO 60,000 FEET

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SUMMARY

Interdependence of intercooler parameters and performance for a pursuit-type airplane using a 1675-horsepower engine is shown at altitudes of 25,000, 36,000, 47,000, and 60,000 feet by means of perspective drawings. Qualitatively, the drawings have general application.

Intercooling between stages of supercharging at high altitudes results in no saving in the power to supercharge and cool the engine air.

INTRODUCTION

The effects of altitudes up to 60,000 feet on the engine cooling systems of liquid-cooled and air-cooled engines have been discussed in reference 1. The purpose of the present report is to consider the effects of altitude on intercooler characteristics and to present a straightforward picture of the interdependence of the intercooler variables. Seven perspective drawings are included which enable an intercooler designer to choose by inspection the intercooler best suited for given operating conditions. It is apparent from the drawings that the present practice of selecting an intercooler on the basis of the cooling-air pressure drop available is not advisable for intercoolers to be used at high altitudes.

The drawings as presented show the values of the various parameters when it is assumed that the intercooling is done after the supercharging has been completed. In actual installations, three stages of supercharging will be required at altitudes of 47,000 and 60,000 feet.

It is shown in appendix A that, if the power required to supercharge and cool the engine air is considered, intercooling between stages of supercharging results in no gain over intercooling after the supercharging is completed. Intercooling between stages of supercharging may be necessary, however, to reduce the maximum engine-air temperature.

Figures are constructed for a representative example of a Harrison louvered aluminum intercooler delivering the engine air for a 1675-normal-cruising-horsepower engine installed in a pursuit-type airplane. Similar charts may be constructed for any installation by the methods shown in appendix B. For an engine of different power using the Harrison louvered aluminum intercooler, the intercooler height, the frontal area for cooling air, and the volume at any altitude may be scaled from the figures presented. Engine-air passage length, cooling-air passage length, pressure drop for cooling air, and ratio of cooling-air to engine-air weight flow are independent of engine power. The figures apply qualitatively to any other type of intercooler for any operating conditions.

A large number of variables are involved in the selection of an intercooler; namely, properties of the air, characteristics of the airplane and airplane engine, weight flow of cooling air, pressure drops of cooling and engine air, power used by the intercooler, and internal and external intercooler dimensions. Many of these variables are determined by considerations other than the intercooler design. A brief discussion of some of the "fixed" variables is included in appendix B.

SYMBOLS

A frontal area of intercooler, square feet

C_D/C_L ratio of drag coefficient to lift coefficient of airplane, dimensionless

L length of air passage, feet

M weight rate of air flow, pounds per second

p static pressure, pounds per square foot or inches of mercury

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Δp	pressure drop, pounds per square foot or inches of mercury
P	power, horsepower
q	dynamic pressure, pounds per square foot or inches of mercury
T	temperature of air, °F
v	intercooler volume, cubic feet
V_o	airplane speed, feet per second
ϵ	weight factor, dimensionless
η	efficiency, dimensionless
ξ	drop in temperature of engine air divided by initial temperature difference, dimensionless
ζ	mean temperature difference between engine air and cooling air divided by initial temperature difference, dimensionless
ρ	air density, slugs per cubic foot
γ	ratio of specific heat at constant volume to specific heat at constant pressure, dimensionless

Subscripts:

ad	adiabatic
c	cooling air
e	engine air
i	initial
n	no-flow direction
o	free-stream condition
t	total
W	weight

The β's, α's, K's, and the primed generalized variables are defined in reference 2.

SELECTION OF INTERCOOLERS

Six Intercooler Variables

Generally, in the selection of an intercooler, the values of six variables are to be determined; namely, the total intercooler power expenditure P_t, the cooling-air pressure drop Δp_c, the ratio of weight flow of cooling air to weight flow of engine air M_c/M_e, and the three linear dimensions L_n, L_e, and L_c. Combinations of these variables of interest to the intercooler designer are the frontal area for cooling air $A = L_e L_n$, the intercooler volume $v = L_e L_n L_c$, and the generalized variable $\Delta p_c{}' =$ constant $\Delta p_c\ (M_c/M_e)$, which represents in nondimensional form the power to force the cooling air through the intercooler.

The relationships among the six variables and the combinations of these variables just mentioned are shown in figures 1 to 7 at four representative altitudes. Total power used by the intercooler, cooling-air pressure drop, frontal area, no-flow length or height, volume, engine air passage length, and cooling-air passage length are all plotted on the same base, M_c/M_e by $\Delta p_c{}'$. Any two of the variables could have been used as the common base, but the two chosen were considered most convenient. The six variables given may be described by four relations. Hence, if any two variables are fixed in value, the values of the other four variables are also fixed.

For a given value of M_c/M_e, minimum power operation at any altitude is at a value of 0.6 for $\Delta p_c{}'$, as is shown in reference 2. The figures do not continue, therefore, to lower values of $\Delta p_c{}'$. The other boundaries of the figures are set by experience as practical limits. In most cases intercoolers of good design will fall near the center of the figures as inspection of the values of the variables will show.

Use of Drawings

Use of the seven figures presented depends on the stage of the design of the airplane. If the dimensions of the intercooler are fixed, inspection of the figures shows the amount of power, the pressure drop, and the cooling-air weight flow that will be required for operation.

If the intercooler designer has freedom of choice of the dimensions, he may choose values of M_c/M_e and $\Delta p_c'$ and tabulate corresponding values of the other variables. If the values are not satisfactory, other values of M_c/M_e and $\Delta p_c'$ may be chosen and the corresponding values of the other variables at these points may be tabulated and compared. The designer may continue this operation until the most suitable combination of variables is obtained.

At altitudes near 25,000 feet, the values of all the variables are relatively small and intercooler selection is not difficult. At higher altitudes, however, the intercooler must be selected very carefully to avoid critical values of the variables. The final selection made by each designer will depend on the relative weight given the different variables.

Selection of an Intercooler at an Altitude of 60,000 Feet

By inspection of the seven figures for an altitude of 60,000 feet, the value of M_c/M_e chosen arbitrarily at 2.5 results in reasonable values of the other variables. At $\Delta p_c' = 0.6$ and $M_c/M_e = 2.5$, the values of the other variables are:

P_t, horsepower	79.0
Δp_c, pounds per square foot.	8.8
A, square feet	26.0
v, cubic feet.	12.6
L_n, feet	5.5
L_e, feet	4.5
L_c, feet	0.60

If M_c/M_e is decreased, P_t, Δp_c, v, L_e, and L_c are increased and, if M_c/M_e is increased, A and L_n increase rapidly. It seems best to reduce the dimensions at the cost of P_t and Δp_c by choosing Δp_c greater than 0.6. If $\Delta p_c'$ is increased from 1.5 to 2.0, however, P_t increases 10.5 horsepower for a corresponding decrease in A of 1.4 square feet. The better designed intercooler may be, therefore, at a $\Delta p_c'$ of 1.5. Values of the variables at $M_c/M_e = 2.5$ and $\Delta p_c' = 1.5$ are:

P_t, horsepower	94.5
Δp_c, pounds per square foot	16.8
A, square feet	15.2
v, cubic feet	9.6
L_n, feet	4.2
L_e, feet	2.3
L_c, feet	0.68

In figure 8 intercooler variables selected by similar compromises are plotted against altitude; $\Delta p_c'$ was chosen as 1.5 at each altitude.

Power cost at various altitudes for the intercoolers designed for 60,000 feet and 25,000 feet is shown in figure 9. The intercooler designed for 25,000 feet will not perform the required cooling above about 50,000 feet. The optimum curve for power of figure 9 does not represent the intercooler of minimum power at a given altitude but represents a compromise of power and the dimensions for the installation.

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APPENDIX A

COMPARISON OF SINGLE-STAGE AND TWO-STAGE INTERCOOLING

The figures presented in the present paper assume that the intercooling is accomplished in a single stage after the engine air has been compressed to 30.3 inches of mercury by a turbosupercharger. At 60,000 feet, the ratio of engine air pressure at the intercooler entrance to atmospheric pressure is 14.4 and the maximum temperature of the engine air is 508° F.

Intercooling between the stages of compression may be considered a means of reducing the maximum engine-air temperature and diminishing the power required to compress the engine air.

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By use of the method outlined in appendix B and by effecting a reasonable compromise on the intercooler parameters as shown in the body of the present paper, intercoolers for two-stage intercooling at an altitude of 60,000 feet have been determined. The difference in power required to compress the engine air for the single-stage and for the two-stage intercooling has also been computed. It has been assumed that the compression of the engine air can be accomplished in three stages of approximately equal compression ratio, that cooling the engine air to 100° F between the second and the third stages is desirable, and that both methods of supercharging can be accomplished at 66 percent adiabatic efficiency.

The parameters of intercoolers at $\Delta p_c' = 1.5$ are as follows:

Stage	P_t (hp)	Δp_c $\left(\frac{lb}{sq\ ft}\right)$	A (sq ft)	v (cu ft)	L_n (ft)	L_e (ft)	L_c (ft)	$\frac{M_c}{M_e}$	Supercharging power (hp)
Between 2 and 3	107.9	23.0	13.9	10.9	4.2	3.3	0.79	2.3	----
After 3	86.4	18.3	12.9	9.3	3.7	3.5	.69	2.3	-----
Total	194.3	----	26.8	20.2	---	---	----	4.6	890
Single	94.5	16.8	15.2	9.6	4.2	2.3	.68	2.5	[a]984

[a]This value includes 11 hp necessary to carry an estimated difference of 100 lb in supercharger weight.

From the power consideration, there is almost no difference in the two methods of intercooling. The single-stage intercooling results in a saving of about 10 cubic feet of intercooler volume, of 165 pounds weight, and of 7.4 pounds per second of cooling air. The two-stage intercooler reduces maximum engine-air temperature from 608° to 375° F.

The figures at 60,000 feet therefore represent the most favorable picture from the consideration of intercooling, but maximum temperature consideration favors the two-stage intercooling installation.

APPENDIX B

METHODS AND SAMPLE CALCULATIONS

The methods of obtaining figures 1 to 7 may be illustrated by determining a typical point at $M_c/M_e = 4$ and $\Delta p_c' = 1.0$ for operating conditions at 60,000 feet.

Calculations are based on Army air. Army air temperature is 40° F above the temperature of NACA standard air at sea level and decreases linearly with altitude to -67° F at about 47,000 feet where the isothermal layer begins. Above 47,000 feet, the properties of Army air and NACA standard air are identical.

Initial engine-air temperature is computed by assuming a compression by a turbosupercharger of 66 percent adiabatic efficiency maintaining constant manifold pressure of 29 inches of mercury at all altitudes considered. The supercharger adiabatic efficiency is defined as

$$\eta_{ad} = \frac{T_o\left[\left(\frac{p_{i_e}}{p_o}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{T_{i_e} - T_o}$$

The velocity of the cooling air through the intercoolers is small in comparison with the airplane speed. The temperature of the cooling air as it enters the intercooler may be computed conveniently and accurately, therefore, by adding full adiabatic compression temperature rise to Army air temperature at a given altitude. The adiabatic temperature rise in °F is

$$\Delta T_{ad} = \frac{1.78V^2}{10^4}$$

where V is given in miles per hour.

Army specifications limit the value of the engine-air pressure drop in the intercooler and connecting ducts to 1.5 inches of mercury. If initial engine-air temperatures and supercharging power are considered, the engine-air pressure drop must be chosen as small as possible. If it is small, however, the intercooler volume will be too large and the intercooler operating power will be excessive. A conservative estimate of the pressure drop in the intercooler itself including the exit loss is 1.0 inches of mercury. This value is used in constructing the charts presented in this report and is satisfactory with respect to low-power intercooler operation for almost all installations.

Initial engine-air pressure is the sum of the carburetor manifold pressure of 29 inches of mercury and a loss of 1.0 inch of mercury in the intercooler and an estimated duct loss of 0.3 inch of mercury, totaling 30.3 inches of mercury.

The amount of cooling-air pressure drop available shown in figure 2 is assumed equal to $0.75q_o$ where q_o (called q_a) is given in figure 13 of reference 1. The average cooling-air pressure for calculation of air density is here estimated by adding 0.9q to the free-stream atmospheric pressure. The weight factor ϵ and cooling-air duct efficiency η_c are estimated.

The values of the engine-air weight flow, the temperature of the engine air as it enters the carburetor, the airplane velocity, the altitude, the impact pressure, and the airplane drag-lift ratio are generally furnished the intercooler designer. Values used in the present report are taken from reference 1.

From the foregoing considerations, intercooler selection form 1, which is based on form 1 of reference 2, has been completed at the four altitudes of figures 1 to 7 to suit the pursuit-type airplane and engine considered.

Other properties of the air, such as density and viscosity, also appear as variables in intercooler selection. Their effect is included in the choice of β_1, β_2, β_3, and β_4 of the sample calculation at 60,000 feet on form 2, which in the present paper is the same as form 5 of reference 3.

Similar calculations of the variables were made for various other values of $\Delta p_c'$ and M_c/M_e to obtain points for plotting figures 1 to 7. The same procedure of calculation can be carried out for any operating conditions to find the variables of the intercooler.

At $M_c/M_e = 4$ and $\xi = 0.849$, from figure 5 of reference 2, $\zeta = 0.335$. The generalized coordinate $\Delta p_e'$ is calculated using the values from form 2 as follows:

$$\Delta p_e' = \frac{\alpha_5 \; K_1 \; M_e \; \zeta \; \Delta p_e}{\alpha_4 \; K_3} = 19.7$$

The intersection of $\Delta p_e' = 19.7$ with $\Delta p_c' = 1.0$ represents the intercooler on the generalized chart for the Harrison louvered aluminum intercooler (fig. 4, reference 2). The values of the other generalized variables are:

$$P' = 2.63$$

$$v' = 1.63$$

$$L_e' = 3.75$$

$$L_n' = 0.30$$

$$L_c' = 1.39$$

The variables are calculated as follows:

$$P_W + P_c = \frac{P'}{550 \; K_1 \; \zeta} = 64.0 \text{ hp}$$

$$v = \frac{v'}{\alpha_5 \; K_1 \; \zeta} = 9.45 \text{ cu ft}$$

$$L_e = \frac{L_e' \; K_2}{\zeta \; K_1 \; M_e \; \alpha_5} = 3.28 \text{ ft}$$

$$L_n = \frac{L_n' \; K_1 \; M_e^{2} (M_c/M_e) \; \zeta}{K_2 \; K_4} = 8.27 \text{ ft}$$

$$L_c = \frac{L_c' \; K_4}{K_1 \; M_e \; (M_c/M_e) \; \zeta} = 0.334 \text{ ft}$$

$$P_e = \frac{0.00137 \; (\bar{T}_e + 460) \; \Delta p_e \; M_e}{\bar{p}_e} = 9.3 \text{ hp}$$

$$P_t = P_W + P_c + P_e = 73.3 \text{ hp}$$

$$\Delta p_c = \frac{\Delta p_c' \times 1.32\, \eta_b\, \bar{p}_o}{K_1\,(\bar{T}_o + 460)\, M_e\, (M_c/M_e)\, \zeta} = 7.43 \text{ lb/sq ft}$$

$$A_c = L_e\, L_n = 27.1 \text{ sq ft}$$

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1. Brevoort, Maurice J., Joyner, Upshur T., and Wood, George P.: The Effect of Altitude on Cooling. NACA ARR, March 1943.

2. Wood, George P., and Tifford, Arthur N.: Generalized Selection Charts for Harrison and Tubular Intercoolers. NACA ARR, Dec. 1942.

3. Wood, George P.: Generalized Selection Charts for Harrison and Tubular Intercoolers. Supplement I - Selection Forms for Harrison Louvered Aluminum Intercoolers. NACA ARR, Dec. 1942.

Intercooler Selection Form 1

Variable	Symbol	Value at altitude of 25,000 ft	36,000 ft	47,000 ft	60,000 ft	Unit
Engine power		1675	1675	1675	1675	hp
Engine-air weight flow	M_e	3.53	3.53	3.53	3.53	lb/sec
Engine-air inlet temperature		245	318	397	608	^{o}F
Engine-air outlet temperature	$T_{e_{out}}$	90	90	90	90	^{o}F
Engine-air inlet pressure		30.3	30.3	30.3	30.3	in. Hg
Engine-air outlet pres. (Estimated)	$p_{e_{out}}$	29.3	29.3	29.3	29.3	in. Hg
Engine-air mean temperature	$\bar{T}_e$	168	204	244	349	^{o}F
Engine-air mean pressure	$\bar{p}_e$	29.8	29.8	29.8	29.8	in. Hg
[1]Airplane velocity	V_o	598	678	770	879	fps
Pressure at altitude		11.1	6.7	4.0	2.1	in. Hg
[1]Impact pressure	q_o	2.9	2.5	2.1	1.5	in. Hg
Cooling-air mean pressure	$\bar{p}_c$	13.7	8.95	5.89	3.45	in. Hg
Temperature at altitude		10	-30	-67	-67	^{o}F
Adiabatic temperature rise		29	38	49	64	^{o}F
Cooling-air inlet temperature		39	8	-16	-3	^{o}F
[2]Cooling-air weight flow	M_c	$1M_e$	$1M_e$	$1M_e$	$4M_e$	lb/sec
[2]Cooling-air mean temperature	T_c	117	122	137	63	^{o}F
$\dfrac{\text{Engine-air temperature drop}}{\text{Initial temperature difference}}$	ξ	0.752	0.736	0.742	0.849	
[1]Weight factor	ϵ	1.5	1.5	1.5	1.5	
Drag-lift ratio	C_D/C_L	.104	.0908	.0800	.0700	
Duct efficiency (cooling air)	η_c	.9	.9	.9	.9	

[1]Values at various altitudes given in reference 1.
[2]A series of values from 1 to 5 is assigned to M_c to construct figs. 1 to 7. The value of T_c depends on the value assigned M_c.

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Intercooler Selection Form 2

(For Harrison aluminum intercoolers)

	Constant			Value
From figure [a]6 at $\bar{T}_c$ and $\bar{p}_c$	β_1			13.20
$704\ \beta_1/\eta_c$		α_1		10,325
From figure 7 at $\bar{T}_c$	β_2			1.927
$1310\ \beta_2$		α_2		2524
From figure 7 at $\bar{T}_e$	β_3			1.790
$1310\ \beta_3$		α_3		2345
From figure 8 at $\bar{T}_e$ and $\bar{p}_e$	β_4			3.79
$3.35\ \beta_4$		α_4		12.7
$25\ \epsilon\ V_0\ C_D/C_L$		α_5		2307
$(\alpha_5/\alpha_1)^{1/3.5}$		α_6		0.651
$\dfrac{5980\alpha_6}{\alpha_2\alpha_5 M_e\ \xi}$			K_1	2.231×10^{-4}
$\left(\dfrac{\alpha_5\alpha_6}{\alpha_3}\right)^{1.25}$			K_2	0.533
$K_2^{2.8}$			K_3	0.172
$\dfrac{\alpha_6^{1.25}}{\alpha_5}$			K_4	2.535×10^{-4}

[a]Figure numbers refer to figures in reference 2.

FIG. 1. VARIATION OF P_t WITH M_c/M_e AND $\Delta P_c'$.

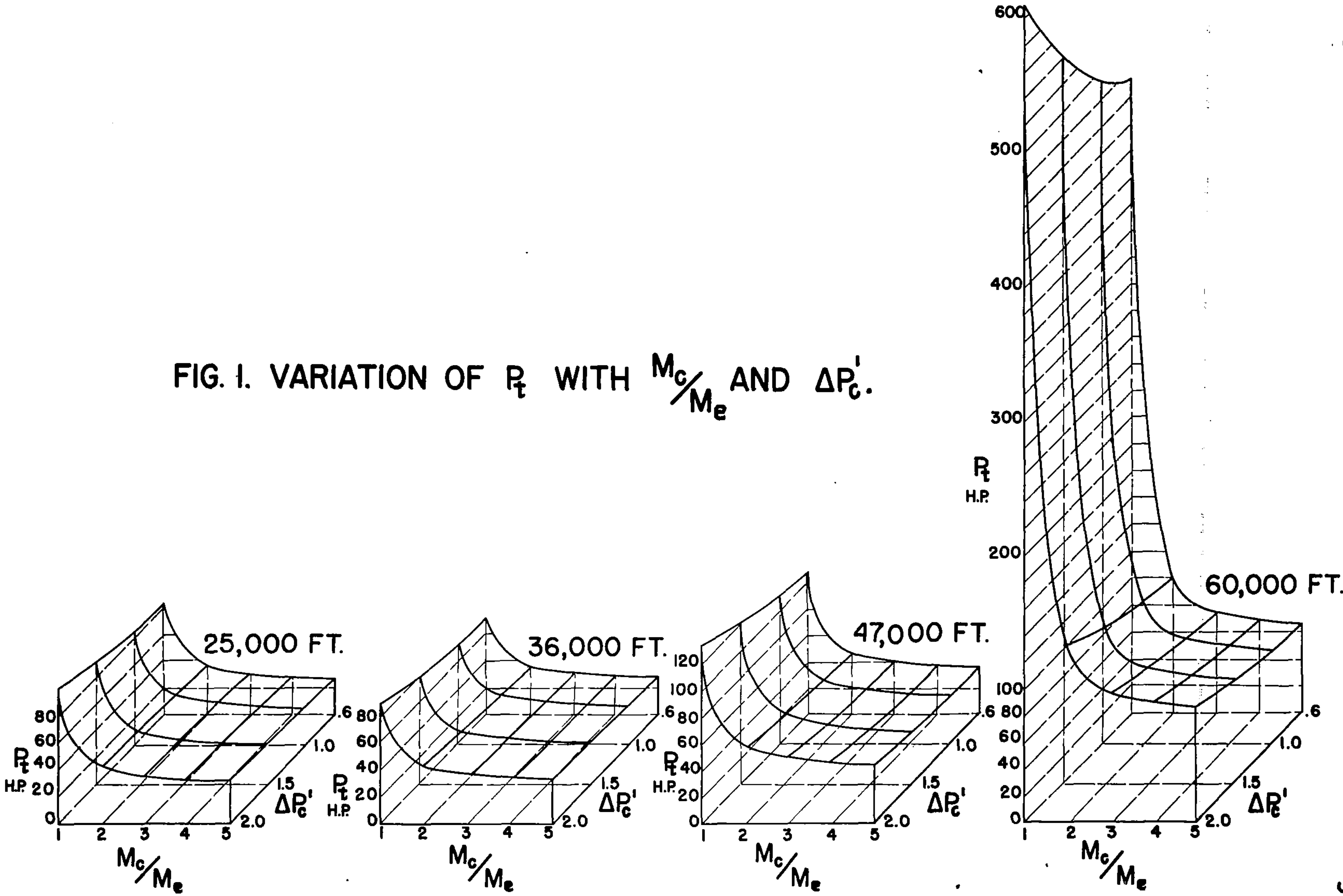

FIG. 2. VARIATION OF ΔP_c WITH M_c/M_e AND $\Delta P_c'$.

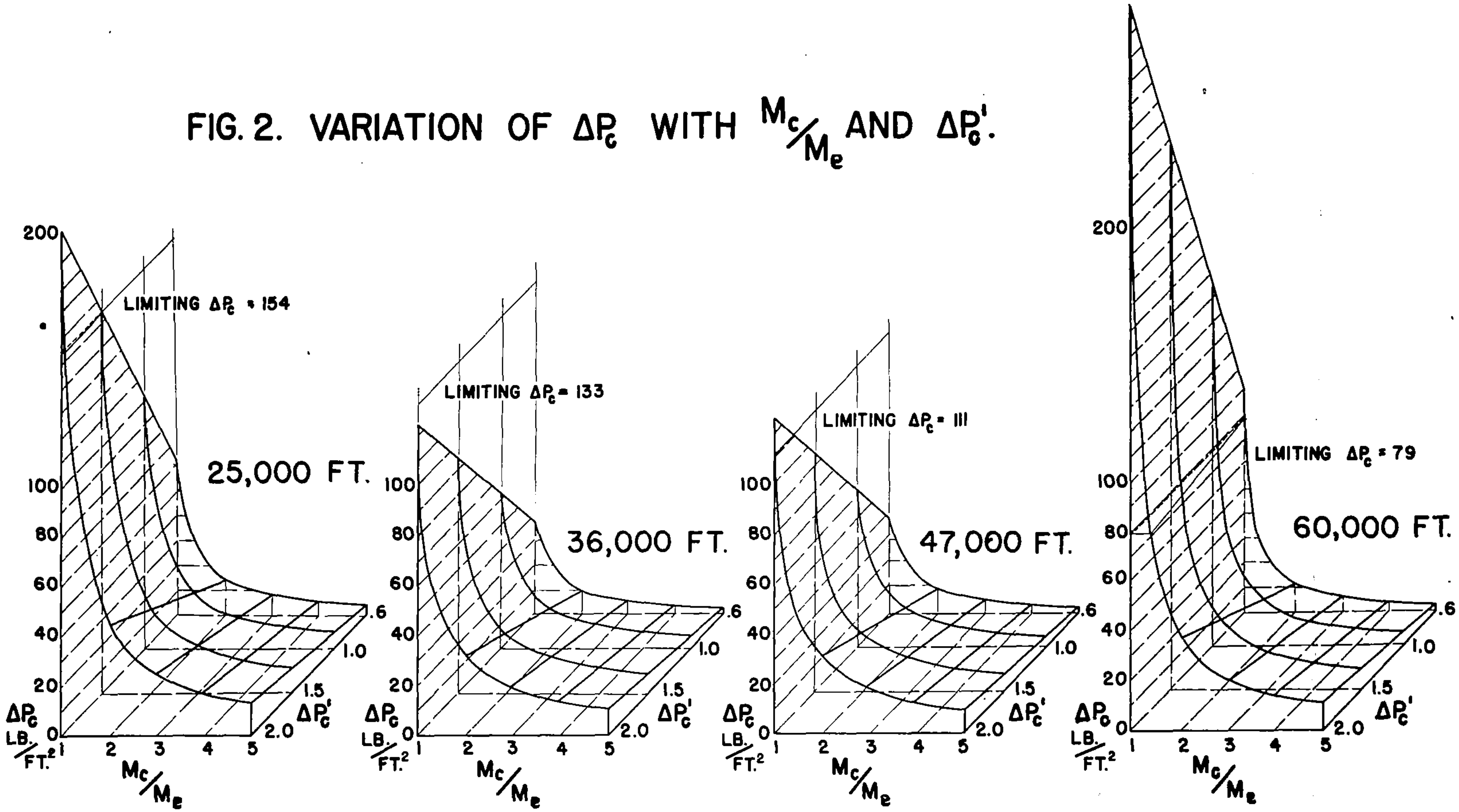

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FIG. 3. VARIATION OF A_c WITH M_c/M_e AND $\Delta P_c'$.

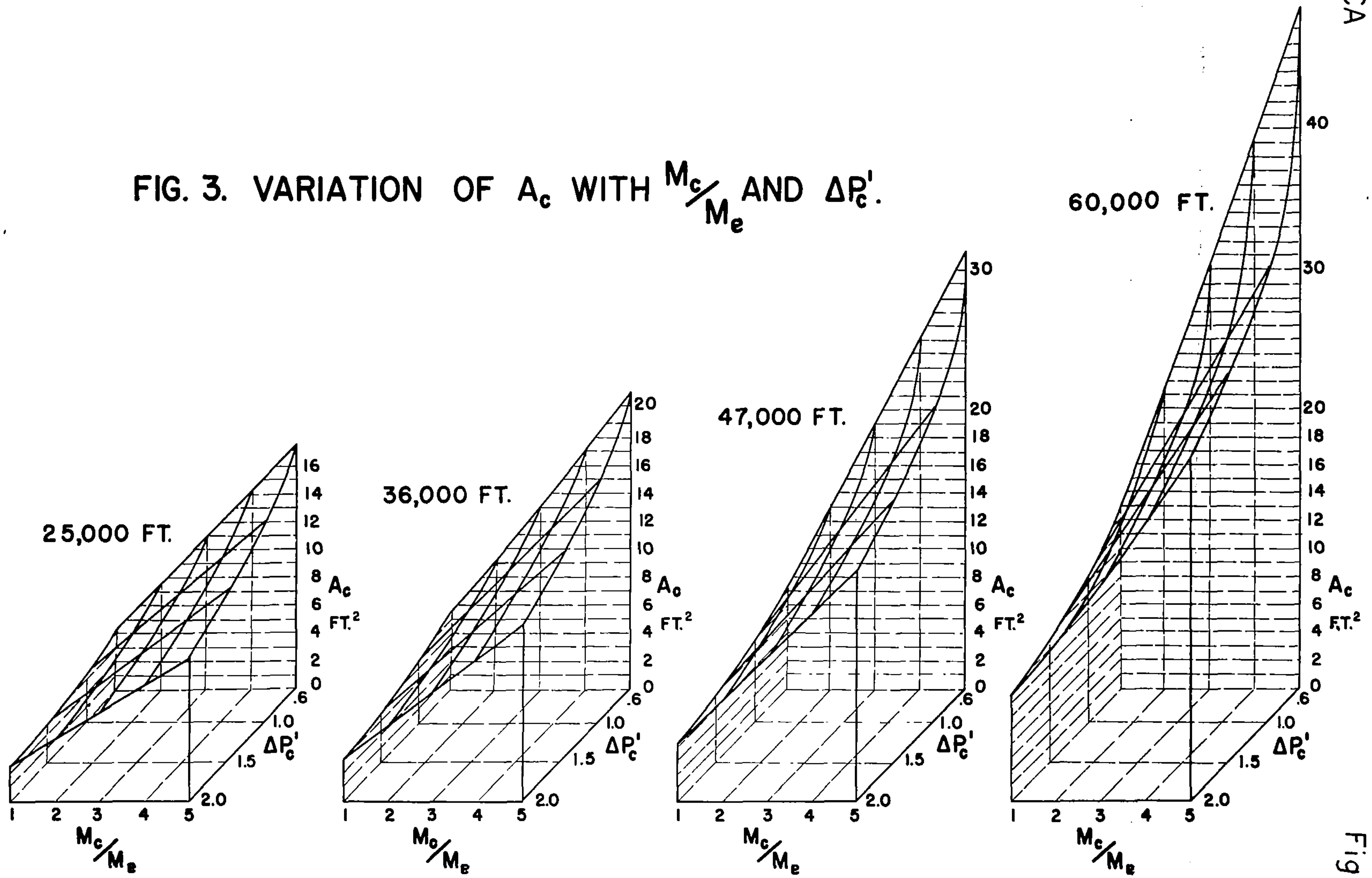

Fig. 3

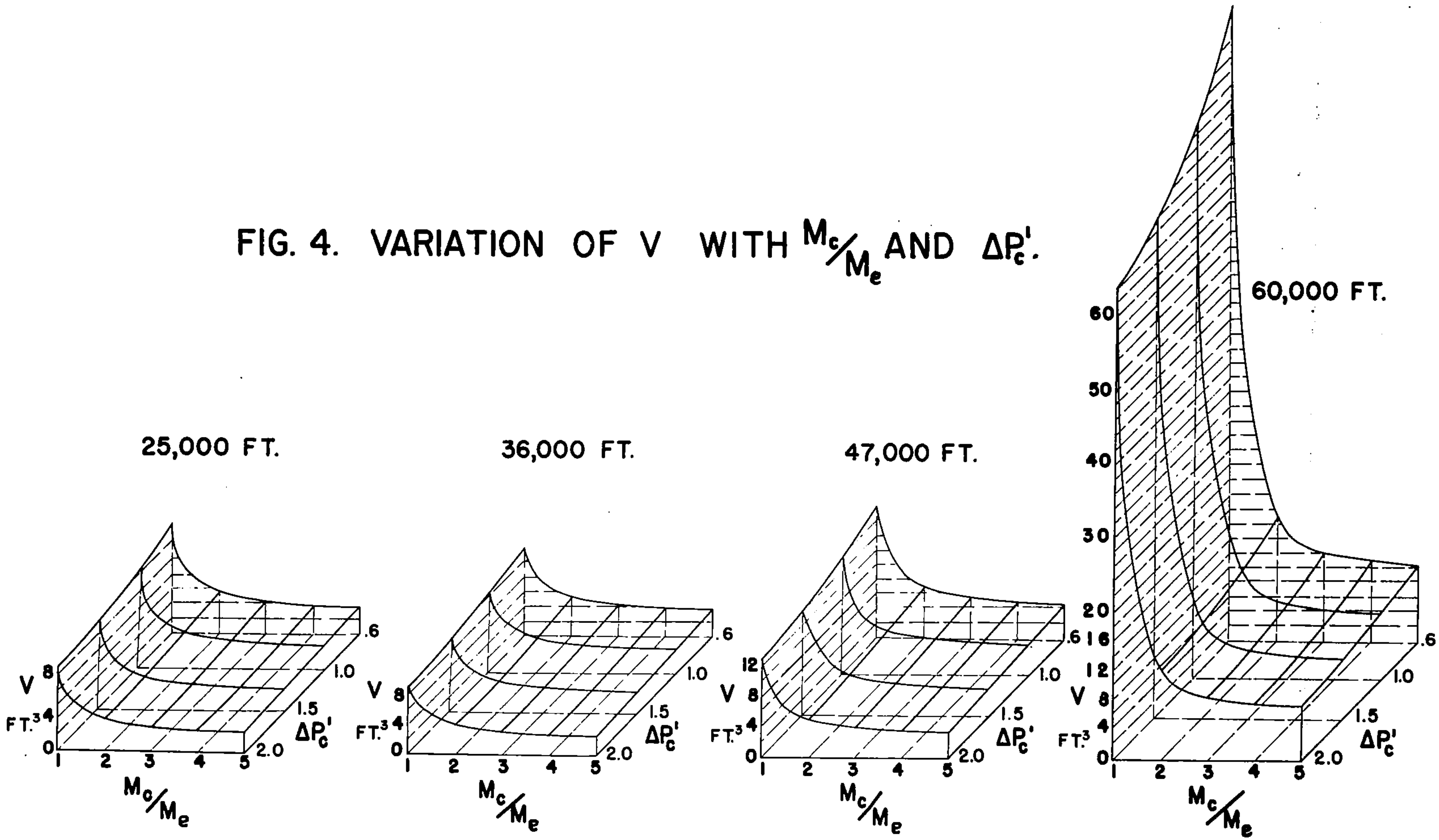

FIG. 4. VARIATION OF V WITH M_c/M_e AND $\Delta P_c'$.

FIG. 5. VARIATION OF L_n WITH M_c/M_e AND $\Delta P_c'$.

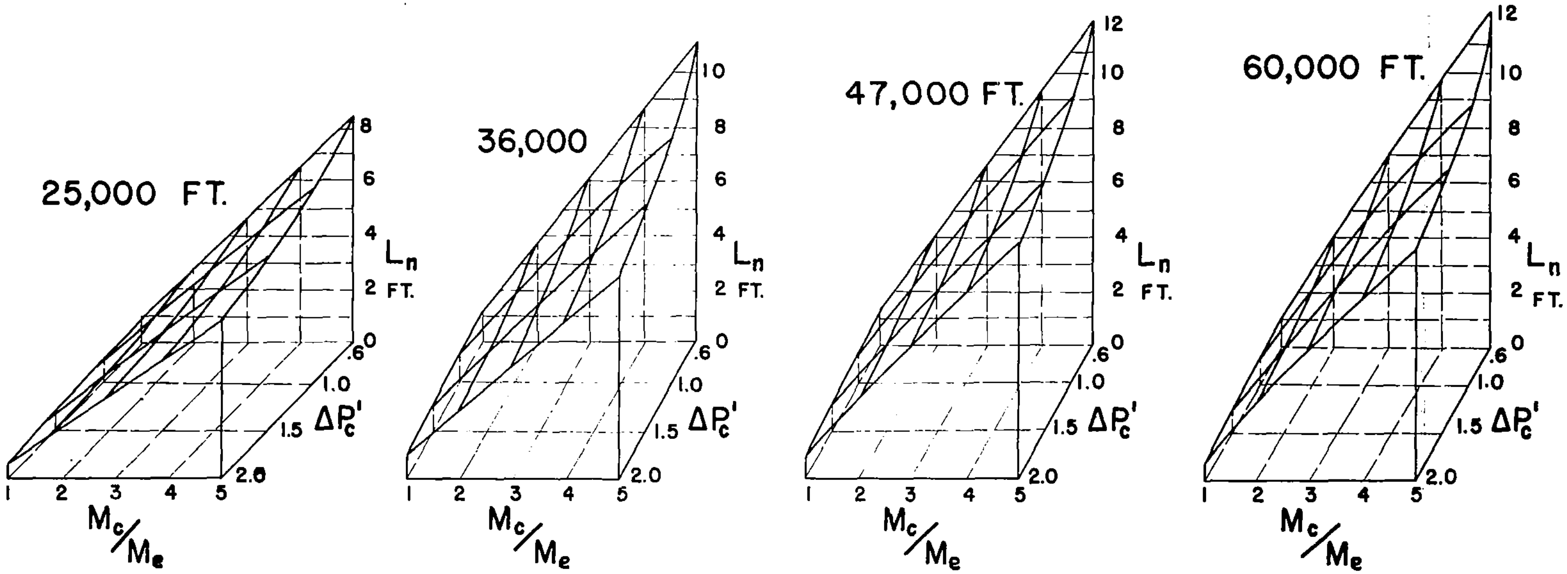

FIG. 6. VARIATION OF L_e WITH M_c/M_e AND $\Delta P_c'$.

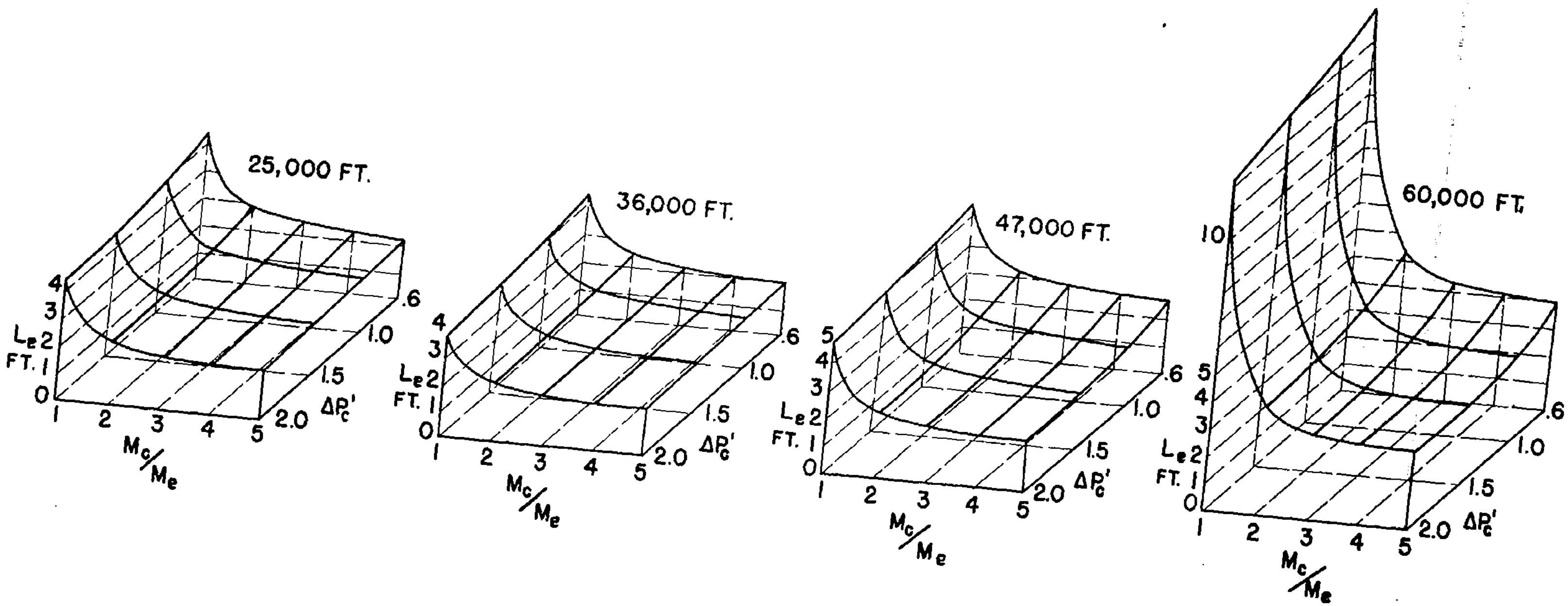

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FIG. 7. VARIATION OF L_c WITH M_c/M_e AND $\Delta P_c'$.

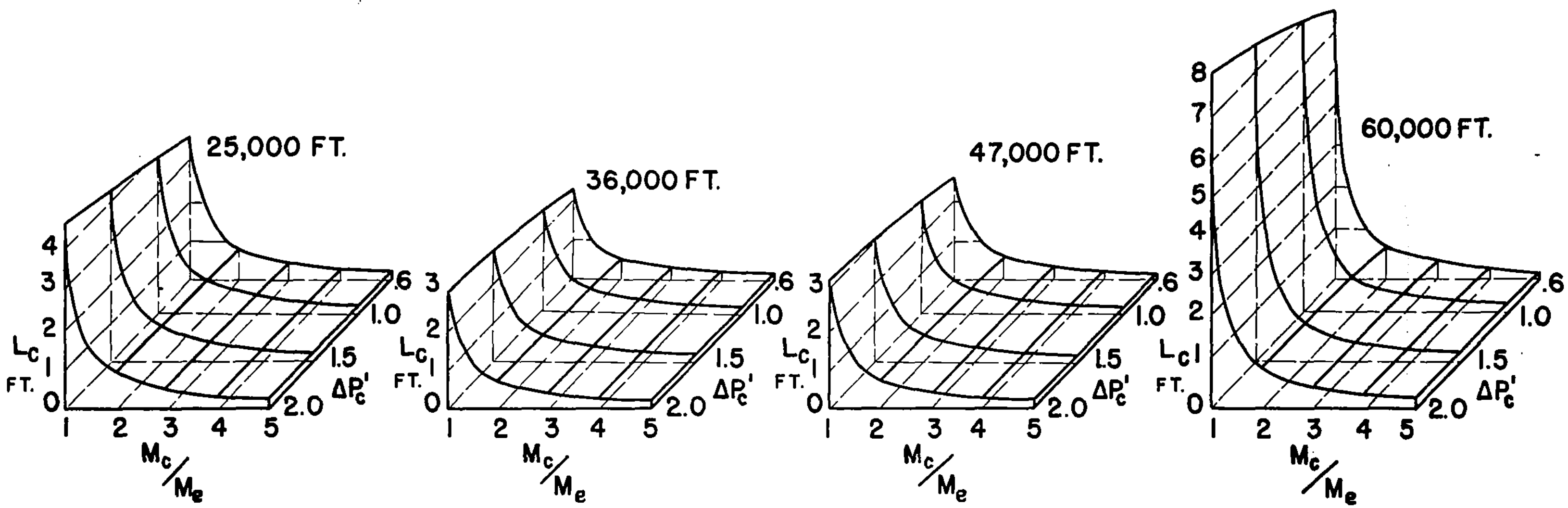

Fig. 7

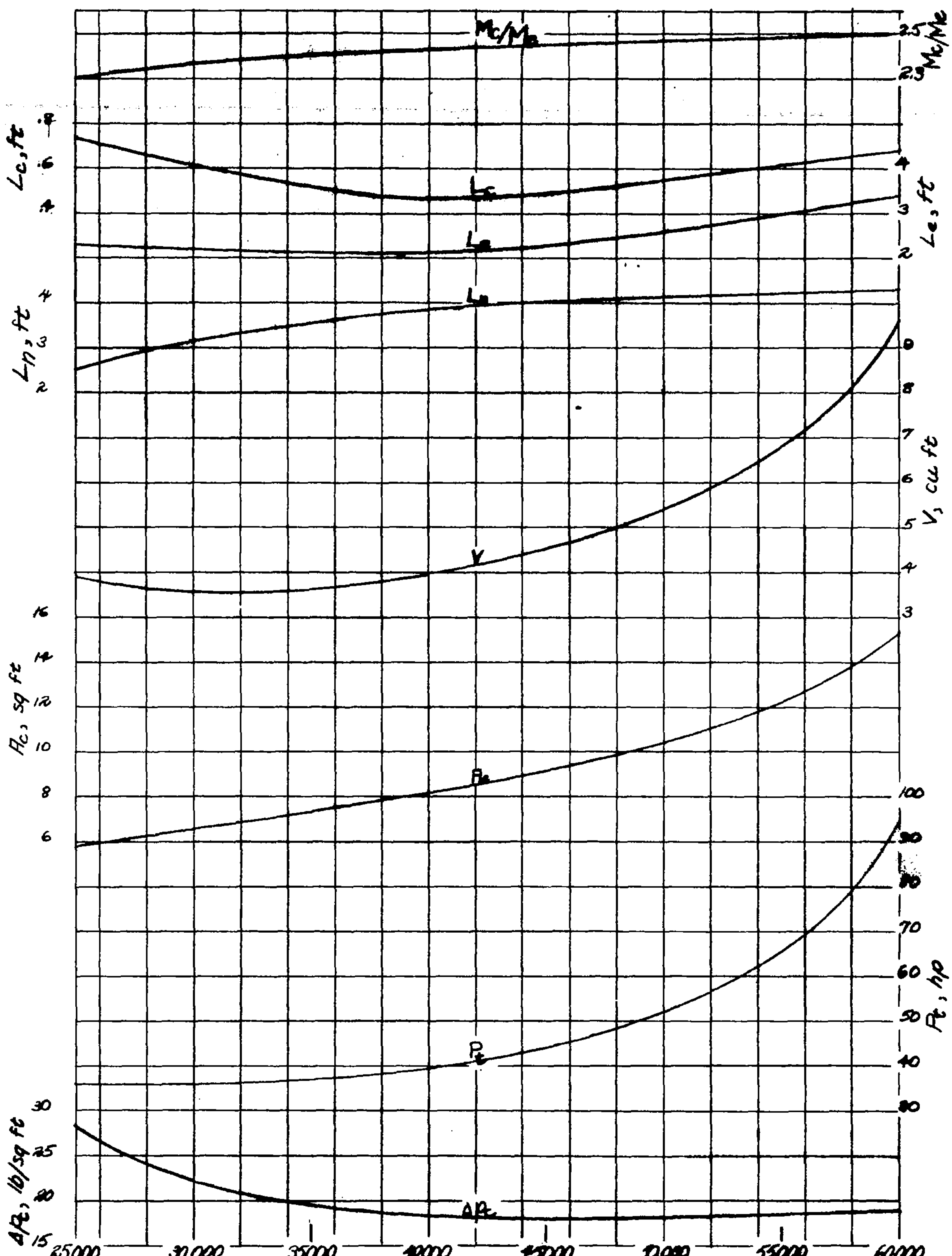

Figure 8.- Variation of intercooler parameters with altitude.

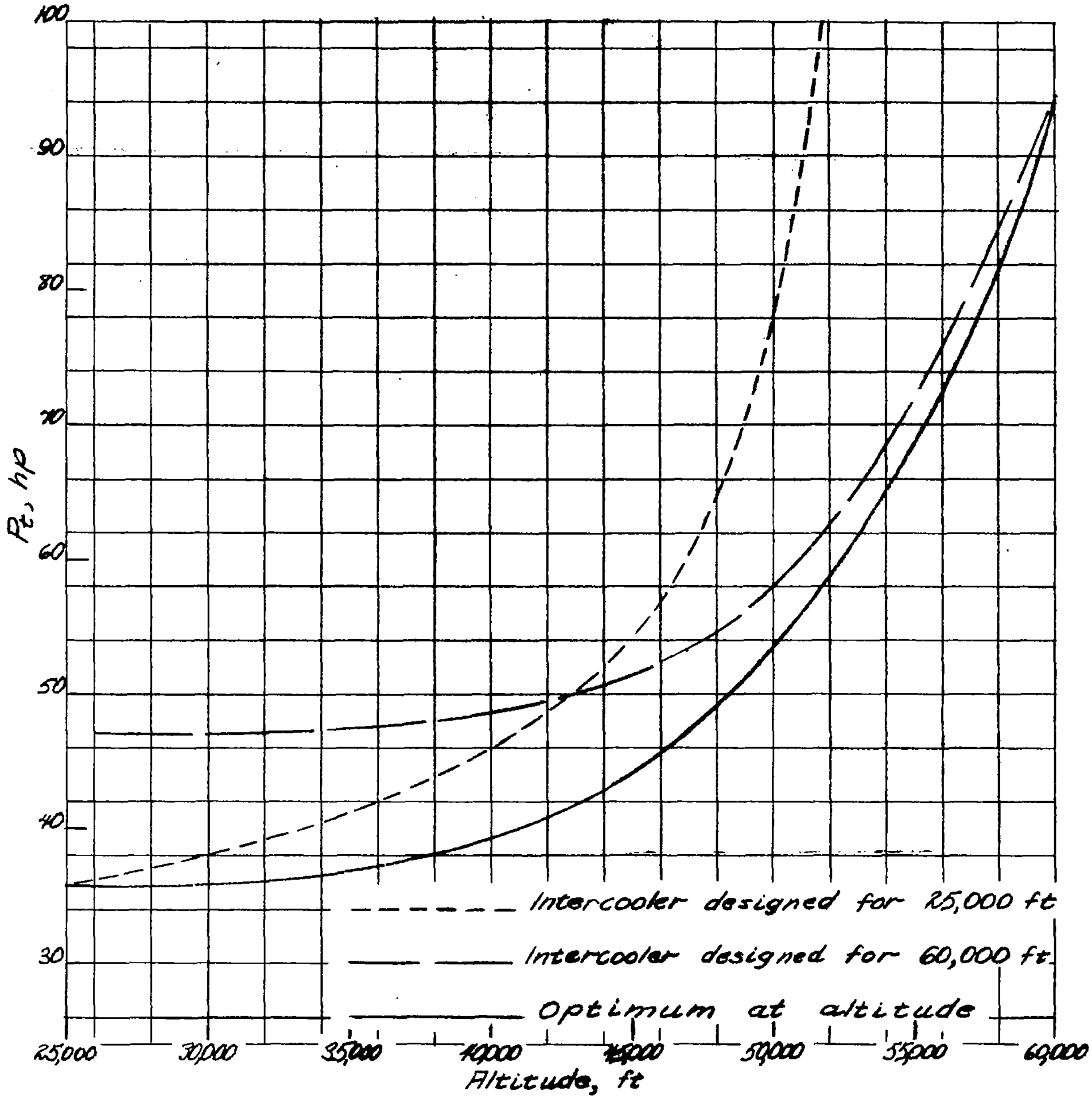

Figure 9.- Variation of P_t of a given intercooler with altitude.